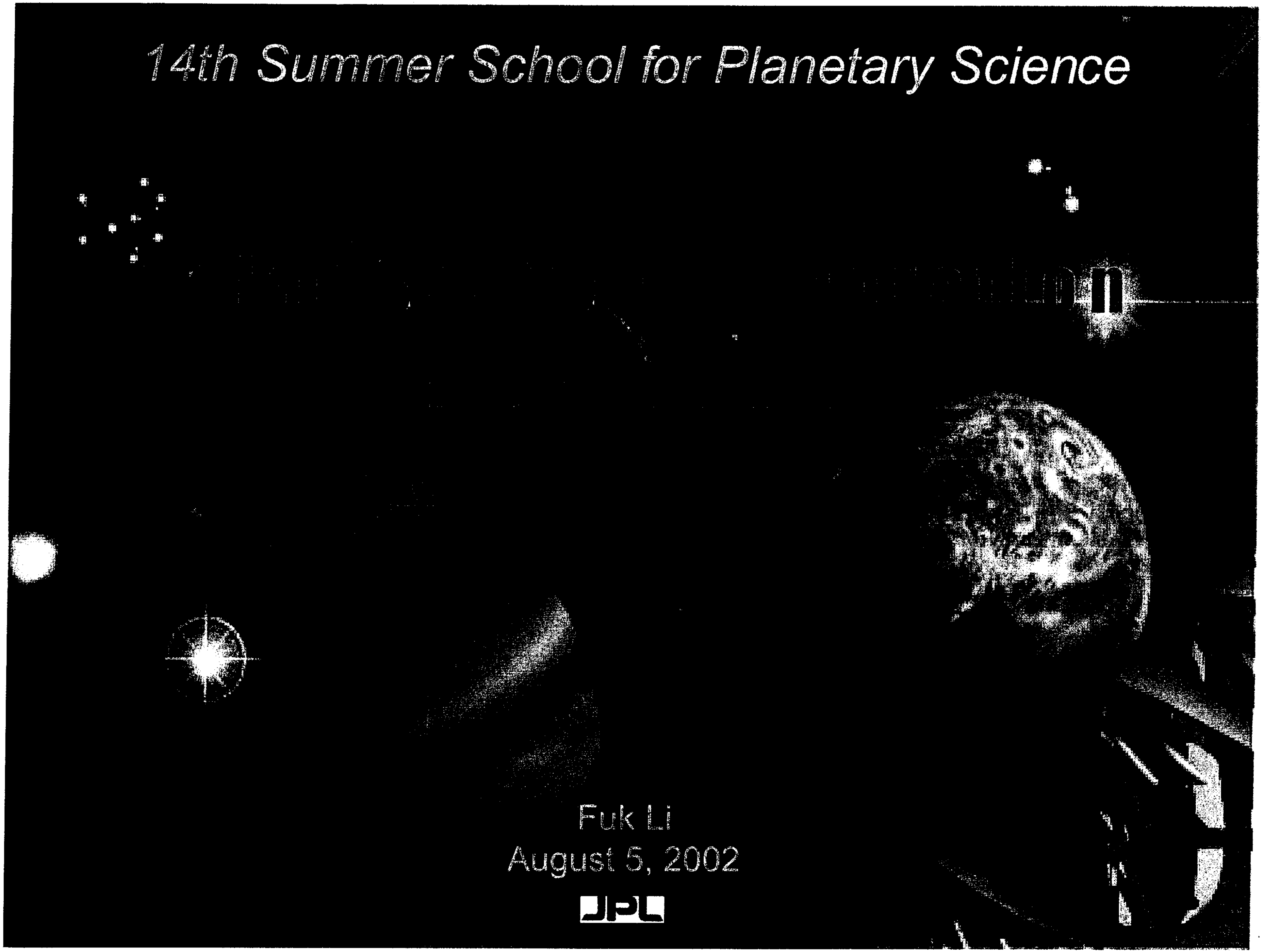
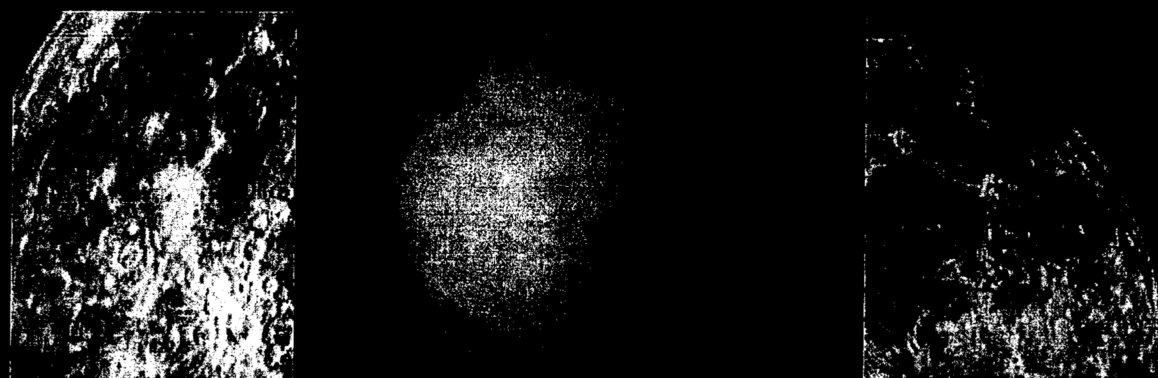

14th Summer School for Planetary Science
Fuk Li
August 5, 2002
JPL

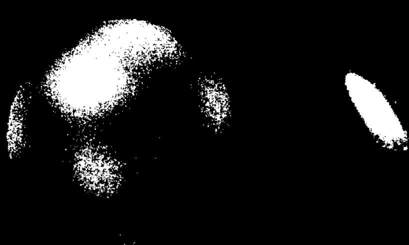

Our Solar System: Forty Years of Exploration
Terrestrial Planets
Comets
The Moon

Exploration of the Solar System: Next Steps

The search for water…and evidence of life?



Planetary Climates and Geology



Building Blocks

Prebiotic Chemistry

Solar System Exploration Advisory Structure

Internal FACA committees

NASA Advisory Council

↓

Space Science Advisory Committee

↓

Solar System Exploration Subcommittee (SSES…one per science theme)

(Consider informal community input)

External, independent committees

National Academy of Sciences/
National Research Council

↓

Space Studies Board (Decadal Survey)

↓

Committee on Planetary and Lunar Exploration (COMPLEX)

(Integrate formal public/community input)

- Space Science Enterprise (Code S): Ed Weiler, Associate Administrator
- Solar System Exploration Division: Colleen Hartman, director

- Committees provide advice on science goals and priorities, mission implications, programmatic issues, and special topics.
- Committees meet 3-4 times per year…FACA meetings are open to the public.
- NASA HQ makes program decisions based on committee advice, budget situation, Congress and Administration priorities, personal judgement, and other factors.

New Frontiers in The Solar System.

An Integrated Exploration Strategy

Solar System Exploration Survey
Space Studies Board
National Research Council

9 July, 2002

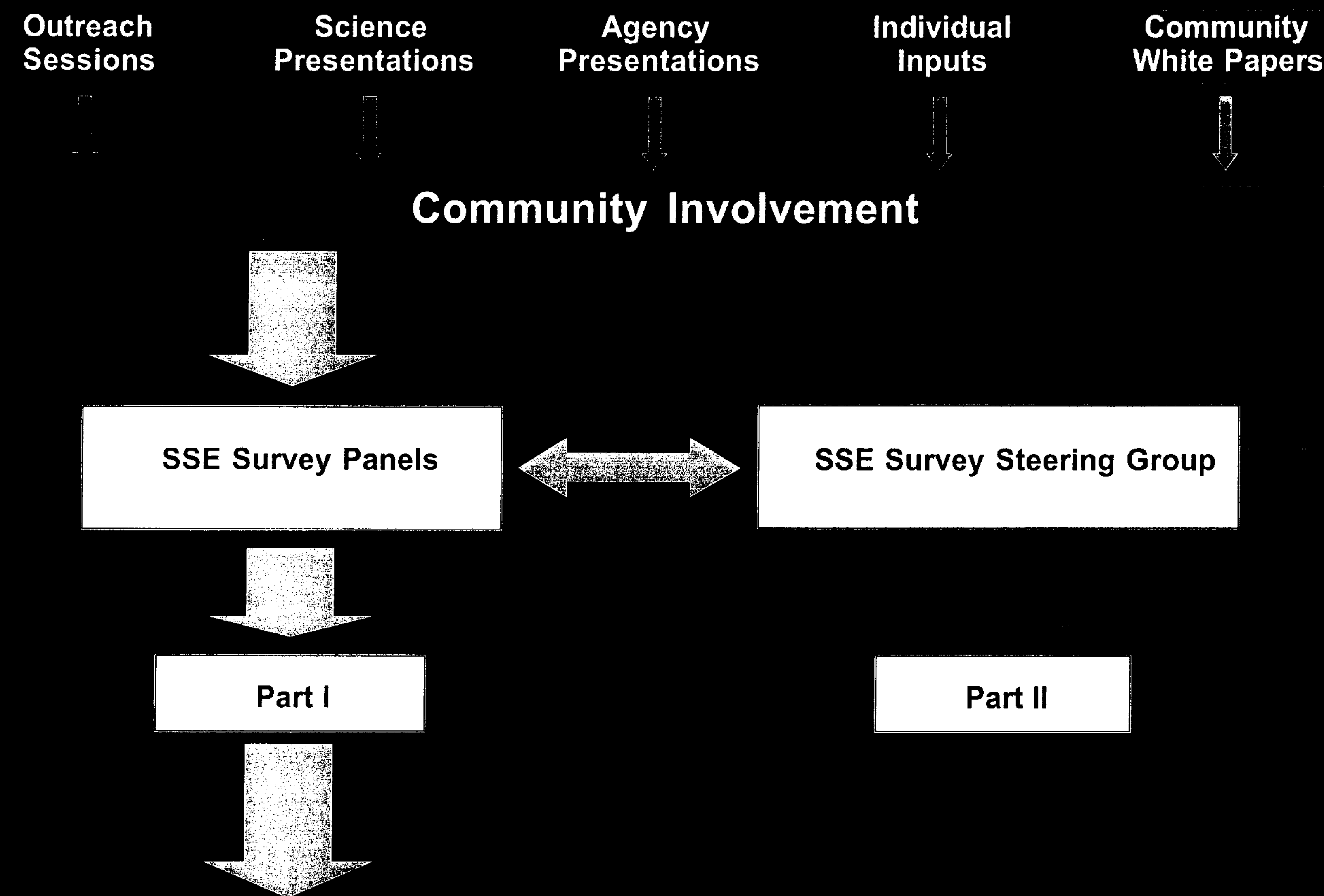
The Charge to the Survey:

¥ **Define a "big picture"** of solar system exploration - what it is, how it fits into other scientific endeavors, and why it is a compelling goal today.

¥ **Conduct a broad survey** of the current state of knowledge about our solar system today.

¥ **Identify the top-level scientific questions** that should provide the focus for solar system exploration today; these will be the key scientific inputs to the roadmapping activity to follow.

¥ **Draft a prioritized list** of the most promising avenues for flight investigations and supporting ground-based activities.



New Frontiers in Solar System Exploration

The Selection and Prioritization Process:

Motivational Goals

▼

Scientific Goals

▼

Scientific Themes and 12 Key Scientific Questions

▼

Mission Selection

▼

Mission Prioritization

Why is Solar System Exploration a Compelling Activity Today:

- **Solar system exploration is that grand human endeavor** which reaches out through interplanetary space to discover the nature and origins of the system of planets in which we live, and to discover whether life exist beyond Earth.

- **It places *within our grasp* answers to questions of profound** human interest:

    - ***Are we alone?***
    - ***Where did we come from?***
    - ***What is our destiny?***

Scientific Goals for Solar System Exploration:

¥ **Determine how life developed in the solar system, where it may** have existed, whether extant life forms exist beyond Earth, and in what ways life modifies planetary environments;

¥ **Understand how physical and chemical processes determine the** main characteristics of the planets, and their environments, thereby illuminating the workings of the Earth;

¥ **Learn how the Sun s retinue of planets originated and evolved;**

¥ **Explore the terrestrial space environment to discover what** potential hazards to the Earth's biosphere may exist;

¥ **Discover how the basic laws of physics and chemistry, acting** over aeons, can lead to the diverse phenomena observed in complex systems, such as planets.

Relationship Between Motivational Questions and Scientific goals

¥ *Are we alone?*

— Determine how life developed in the solar system, where it may have existed, whether extant life forms exist .

¥ *Where did we come from?*

— Learn how the Sun s retinue of planets originated and evolved.

— Discover how the basic laws of physics and chemistry, acting over aeons, lead to diverse phenomena

¥ *What is our destiny?*

— Explore the terrestrial space environment to discover what potential hazards

— Understand how physical and chemical processes determine the main characteristics of the planets

Scientific Themes for 2003 — 2013:

- The first billion years of solar system history
- Volatiles and organics: The stuff of life
- The origin and evolution of habitable worlds
- Processes: How planetary systems work

Relationship Between Scientific goals and Scientific Themes:

Determine how life developed in the solar system, where it may have existed, whether extant life forms exist .

Learn how the Sun s retinue of planets originated and evolved.

Discover how the basic laws of physics and chemistry, acting over aeons, lead to diverse phenomena

Understand how physical and chemical processes determine the main characteristics of the planets

- —The first billion years of solar system history
- —Volatiles and organics: The stuff of life
- —The origin and evolution of habitable worlds
- —Processes: How planetary systems work

Explore the terrestrial space environment to discover what potential hazards

- —The origin and evolution of habitable worlds

Twelve Key Scientific Questions → Missions:

The first billion years of solar system history - - -

- ¥ What processes marked the initial stages of planet formation?
  - ¥ Comet surface sample return (CSSR)
  - ¥ Kuiper belt/Pluto (KBP)
  - ¥ South pole Aitken basin sample return (SPA-SR)
- ¥ Over what period did the gas giants form, and how did the birth of the ice giants (Uranus, Neptune) differ from that of Jupiter and its gas-giant sibling, Saturn?
  - ¥ Jupiter polar orbiter with probes (JPOP)
- ¥ How did the impactor flux decay during the solar system s youth, and in what ways(s) did this decline influence the timing of life s emergence on Earth?
  - ¥ Kuiper belt/Pluto (KBP)
  - ¥ South pole Aitken Basin sample return (SPA-SR)

Twelve Key Scientific Questions → Missions:

Volatiles and Organics: The stuff of life- - -

- **What is the history of volatile compounds, especially water, across our solar system?**
  - Comet Surface Sample Return (CSSR)
  - Jupiter Polar Orbiter with Probes (JPOP)
- **What is the nature of organic material in our solar system and how has this matter evolved?**
  - Comet Surface Sample Return (CSSR)
  - Cassini Extended mission (CASx)
- **What global mechanisms affect the evolution of volatiles on planetary bodies?**
  - Venus In-situ Explorer (VISE)
  - Mars Upper Atmosphere Explorer (MAO)

Twelve Key Scientific Questions → Missions:

The origin and evolution of habitable worlds- - -

- What planetary processes are responsible for generating and sustaining habitable worlds, and where are the habitable zones in our Solar System?
  - Europa Geophysical Explorer (EGE)
  - Mars Smart Lander (MSL) ¥ Mars Sampe Return (MSR)

- Does (or did) life exist beyond the Earth?
  - Mars Sample Return (MSR)

- Why have the terrestrial planets differed so dramatically in their evolutions?
  - Venus In-situ Explorer (VISE) ¥ Mars Smart Larder (MSL)
  - Mars Long-lived Lander Network (MLN) ¥Mars Sample Return (MSR)

- What hazards do solar system objects present to Earth s biosphere?
  - Large-aperture Synoptic Survey Telescope (LSST)

Twelve Key Scientific Questions: Missions:

Processes: How planetary systems work- - -

¥ **How do the processes that shape the contemporary character of planetary bodies operate and interact?**

- ¥ Kuiper Belt / Pluto (KBP) ¥ South Pole Aitken Sample Return (SPA-SR)
- ¥ Cassini Extended mission (CASx) ¥ Jupiter Polar Orbiter with Probes (JPOP)
- ¥ Venus In-situ Explorer (VISE) ¥ Comet Surface Sample Return (CSSR)
- ¥ Europa Geophysical Explorer (EGE)
- ¥ Mars Smart Lander (MSL) ¥ Mars Upper Atmosphere Orbiter (MAO)
- ¥ Mars Long-lived Lander Network (MLN) ¥ Mars Sampb Return (MSR)

¥ **What does our solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?**

- ¥ Kuiper Belt / Pluto ¥ Jupiter Polar Orbiter with Probes (JPOP)
- ¥ Cassini Extended mission (CASx)
- ¥ Large-aperture Synoptic Survey Telescope (LSST)

Solar System Mission Priorities:

¥ *Small Class (<$325M)*

— Discovery missions at one launch every 18 months

— Cassini Extended mission (CASx)

¥ *Medium Class (<$650M) — New Frontiers*

— Kuiper Belt/Pluto (KBP)

— South Pole Aitken Basin Sample Return (SPA-SR)

— Jupiter Polar Orbiter with Probes (JPOP)

— Venus In-situ Explorer (VISE)

— Comet Surface Sample Return (CSSR)

¥ *Large Class (>$650M)*

— Europa Geophysical Explorer (EGE)

Mission Priorities: Mars Flight Missions (beyond 2005):

- *Small Class (<$325M)*
  - —**Mars Scout Line**
  - —**Mars Upper Atmosphere Orbiter (MAO)**
- *Medium Class (<$650M) — New Frontiers*
  - —**Mars Smart Lander (MSL)**
  - —**Mars Long-lived Lander Network (MLN)**
- *Large Class (>$650M)*
  - —**Mars Sample Return preparation so that *its implementation can occur early in the decade 2013-2023* (MSR)**

Missions: Key Scientific Questions:

Kuiper Belt / Pluto (KBP)

A flyby mission of several Kuiper Belt objects, including Pluto/Charon, to discover their physical nature and determine the collisional history of the Kuiper Belt.

¥ What processes marked the initial stages of planet formation?

¥ How did the impactor flux decay during the solar system s youth, and in what ways(s) did this decline influence the timing of life s emergence on Earth?

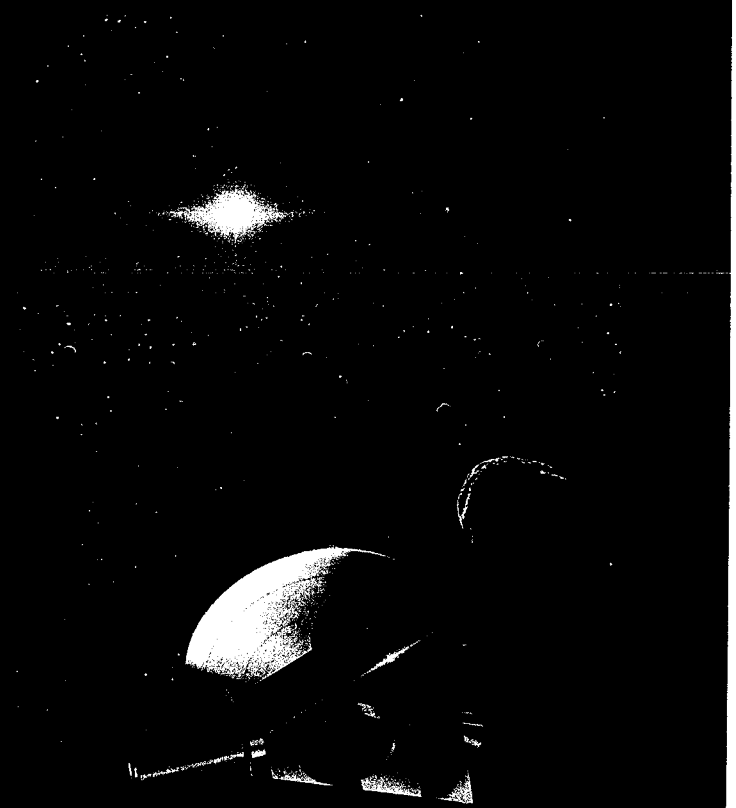
¥ How do the processes that shape the contemporary character of planetary bodies operate and interact?

¥ What does our solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?

Kuiper Belt / Pluto (KBP)

GOALS:

- —Investigate the diversity of the physical and compositional properties of Kuiper belt objects
- —Perform a detailed reconnaissance of the properties of the Pluto-Charon system
- —Assess the impact history of large (Pluto) and small KBOs



Venus *In Situ* Exploration

Objective

- Conduct Venus surface/atmosphere measurements
- Validate techniques for future Venus surface sample return

Mission scenario (planning baseline)

- Launch Dec 2008, Delta 4, significant margins
- Single s/c, direct Venus entry using aeroshell
- Free-fall descent, atmospheric science and descent imaging. Landing at 3-5 m/s
- Surface science/sampling during ~1hour on surface, passive thermal control
- Balloon ascent to ~70 km for sample analysis (possibly including age dating) and telecom direct to Earth. Minimal data return from surface.
- Balloon mission continues for ~3 days

Mission Options

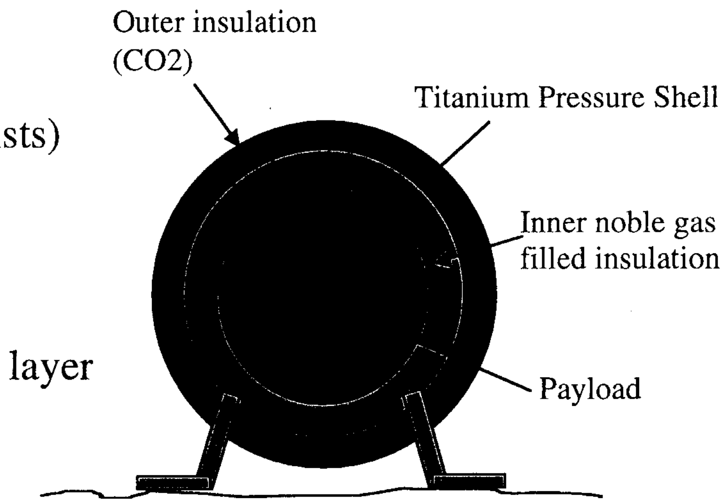
- Lander delivery from Venus orbit
  - Improves site selection and delivery accuracy but adds cost
  - Insertion into orbit via aerocapture would validate additional technology for VSSR but is not required for precursor science mission
- Extend surface survival time to cover primary data relay instead of raising to altitude
  - Reduces risk that balloon failure could compromise primary science goals
  - Significant mass and cost impact to increase surface survival; not required for VSSR
  - Balloon inflation and ascent is a major element of future VSSR mission

Solar System Exploration

Venus *In Situ* Exploration

Major or Unique Developments Required

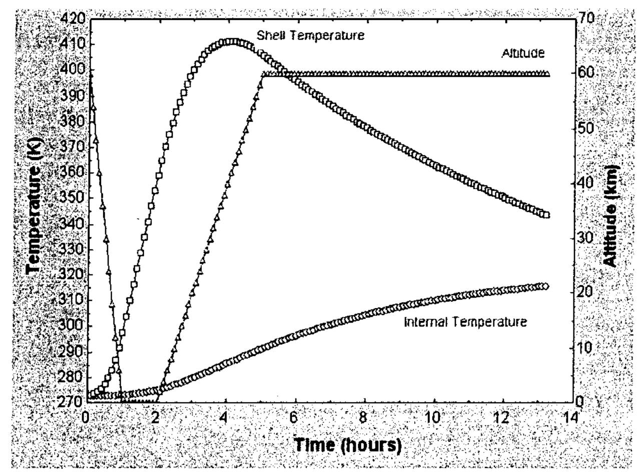
- Miniaturized *in situ* instruments
  - Miniaturized, high-accuracy GCMS (prototype exists)
  - Miniaturized age dating system (Rb-Sr)
  - Other instruments (XRF, DISR) are heritage
- Insulation system for survival on Venus surface
  - Pressure vessel with CO2 outer layer and Xe inner layer
- Super-pressure helium balloon materials/systems
  - Teflon-coated polybenzaxozole (PBO) lab tested
  - Two-stage balloon inflation for safe ascent
- Sample acquisition and handling
  - Ultrasonic drill prototype exists
  - Sample transfer at Venus surface pressure



Thermal protection schematic

Heritage and Commonality

- Mars Pathfinder cruise system and aeroshell design
- Viking XRF, Huygens descent imager/radiometer
- Pioneer/Venus, VEGA/Venera thermal and balloon
- Ultrasonic drill common with MSR, CNSR
- Miniature *in situ* instruments widely applicable



Lander system temperature profile

Solar System Exploration

Venus *In Situ* Exploration

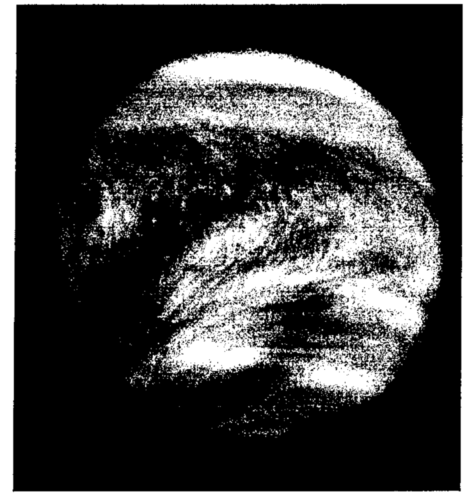
Comments and Issues

- Mission must achieve the proper balance of science and technology objectives

Key VSSR Technologies

Included	Not Included
Aeroshell entry/descent	Aerocapture/ballute
Surface survival - passive	Ascent vehicle
Drill sample acquisition	
Sample transfer	
Balloon ascent/mobility	

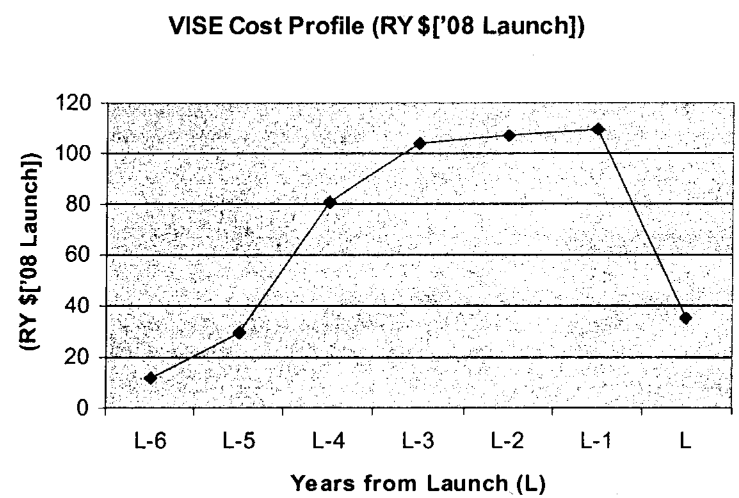
- Development of *in situ* age dating is the most challenging objective, but this mission can achieve important science/technology objectives without that measurement
- Increasing data return from surface (prior to balloon inflation) is a near-term study goal
- Technology development investment of ~$50M will significantly benefit other missions
- Mission class: Moderate
- Technology risk: Moderate to high



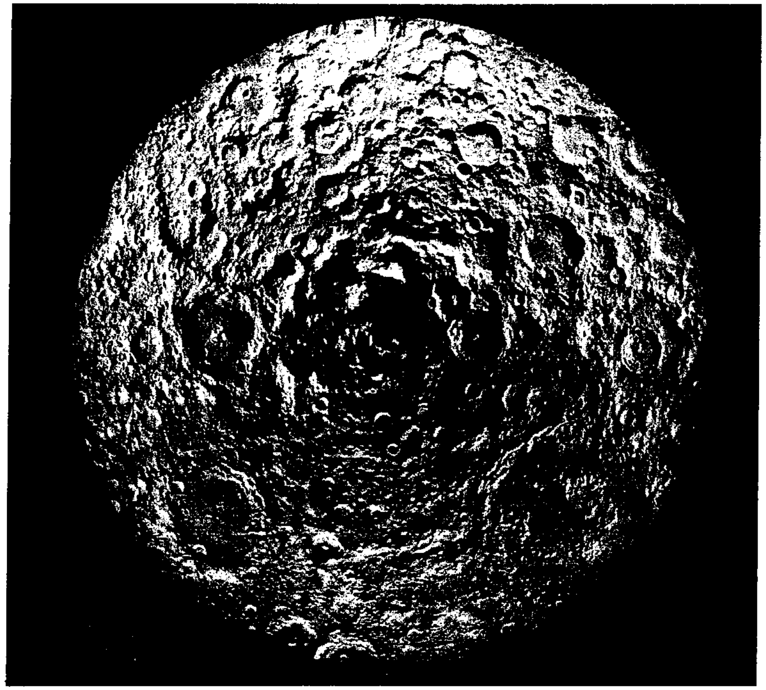
Cost (RY$, FY08 launch)

Development/launch:	$460 - 525M
Mission operations:	$20 - 30M

Multimission technology: ~$25M



Lunar Giant Basin Sample Return



Objective

- Collect and return samples of lunar mantle material from the floor of the South Pole - Aitken basin

Mission scenario (planning baseline)

- Orbiter/lander/rover launched on single Atlas III
- Direct descent trajectory, orbiter diverts to L2 Lagrange point for data relay
- 14 days lunar surface operations
- Subsurface sampling to 2 meters
- Sample collection via tele-operated rover
- Lunar ascent vehicle (LAV) launches 4.6 kg of samples into high Earth orbit
- Orbiter rendezvous with sample return vehicle, sample is transferred to entry vehicle for sample reentry

Mission Options

- Launch sample directly to Earth - no rendezvous in Earth orbit
  - Avoids rendezvous issues and sample transfer, but requires larger launch vehicle
- Rendezvous in lunar orbit
  - Mass penalty due to lunar orbit insertion and escape
- Earth return using aero-entry ballute
  - Reduces entry vehicle mass and orbiter size, but requires technology development
- Link to Earth using Ka-band

Lunar Giant Basin Sample Return

Major or Unique Developments Required

- Soft lunar landing requires development of a throttleable, bipropellant main engine
- Sample collection and handling
  - 2-m deep drill and sample retrieval system on lander
  - Sample cache on rover is brought into sample container on lander
- Tele-operated sample selection
  - Rover carries monochrome imaging, visible and near infrared point spectrometer and X-ray fluorescence for sample selection
  - Sampling decisions must be made on Earth in real time
- Ascent from lunar surface
  - Single-stage, solid rocket motor, spun-up from lunar lander
- Rendezvous and sample transfer in Earth orbit

Heritage and Commonality

- Rover design heritage from Mars missions
- Mars sample return design heritage for rendezvous and sample capture
- Sample curation and analysis facilities exist
- Descent engine could be used at other airless bodies (if low mass)

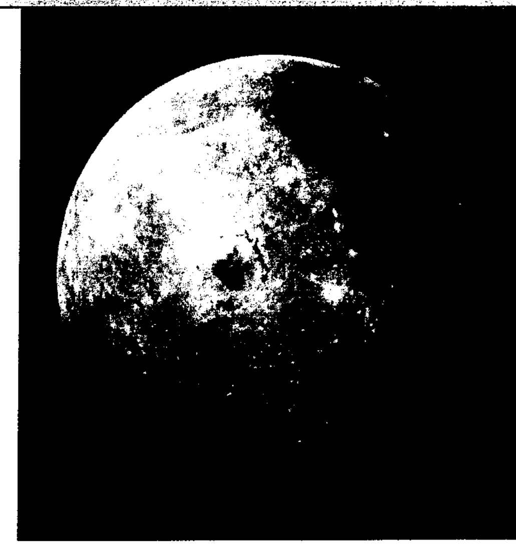
Solar System Exploration

Lunar Giant Basin Sample Return

Comments and Issues

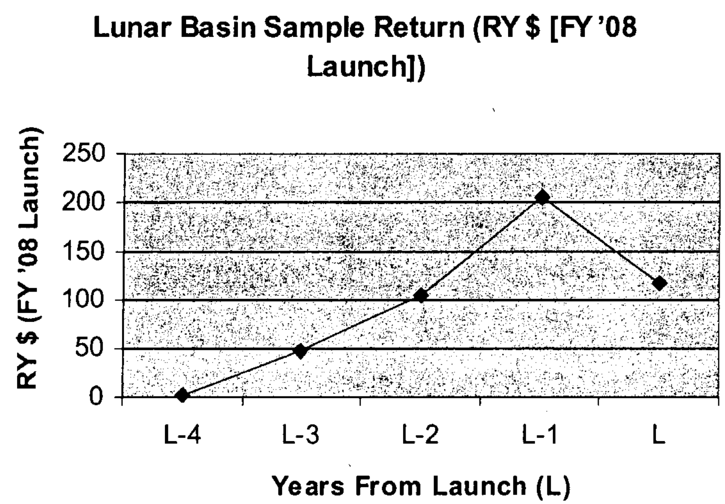
- Rendezvous in Earth orbit vs. direct return or lunar orbit is a key mass/cost/risk trade
- Real-time commanding of orbital and surface elements during critical operations
- Surface mission duration limited by power
- LAV orbit injection accuracy is a concern. Additional propellant needed on the orbiter/rendezvous vehicle to accommodate injection errors.

- Mission class: Moderate
- Technology risk: Low to Moderate
- Multimission technology: ~$12M



Cost (RY$, FY08 launch)

Life-cycle cost: $450 - $600M (model: $480M)



Missions: Key Scientific Questions:

Jupiter Polar Orbiter with Probes (JPOP)

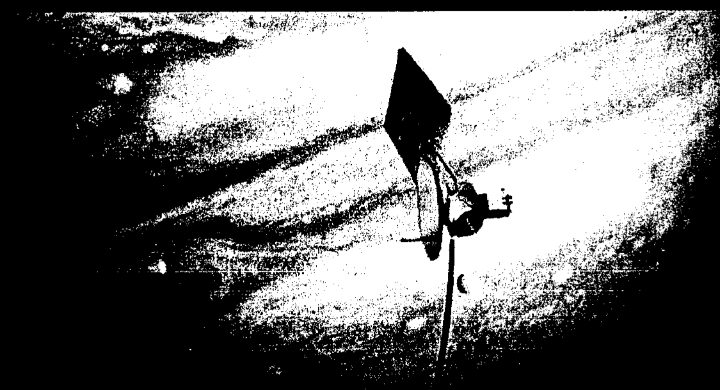
A close-orbiting polar spacecraft equipped with various instruments and a relay for three probes that make measurements below the 100+bar level.

- ¥ Over what period did the gas giants form, and how did the birth of the ice giants (Uranus, Neptune) differ from that of Jupiter and its gas-giant sibling, Saturn?
- ¥ What is the history of volatile compounds, especially water, across our solar system?
- ¥ How do the processes that shape the contemporary character of planetary bodies operate and interact?
- ¥ What does our solar system tell us about the development and evolution of extrasolar planetary systems, and *vice versa?*

Jupiter Polar Orbiter with Probes (JPOP)

GOALS:

- Determine if Jupiter has a central core to constrain ideas of its formation
- Determine the planetary water abundance
- Determine if the winds persist into Jupiter's interior or are confined to the weather layer
- Assess the structure of Jupiter's magnetic field to learn how the internal dynamo works
- Measure the polar magnetosphere to understand its rotation and relation to the aurora



Comet Nucleus Sample Return

Objective

Return pristine samples of volatile materials from a comet nucleus for analysis on Earth

Mission scenario (planning baseline)

- Rendezvous with and orbit an active short-period comet using SEP
- 30-day mapping for site selection; separate lander descends to surface
- Anchor and drill samples from >1 meter depth, minimum 2 sites, rendezvous with orbiter
- Samples maintained cryogenic during Earth return (SEP) and direct ballistic entry

Mission Options

- "Full science" with drilling to ≥1 m at multiple sites, well documented, vs. surface "grab sample"
  - Major implications for science return and cost

- Single or dual spacecraft (separable lander)
  - Dual s/c reduces risk to orbiter due to comet environment and simplifies landing site selection
  - Additional flight system (lander) increases cost and requires rendezvous/capture for Earth return

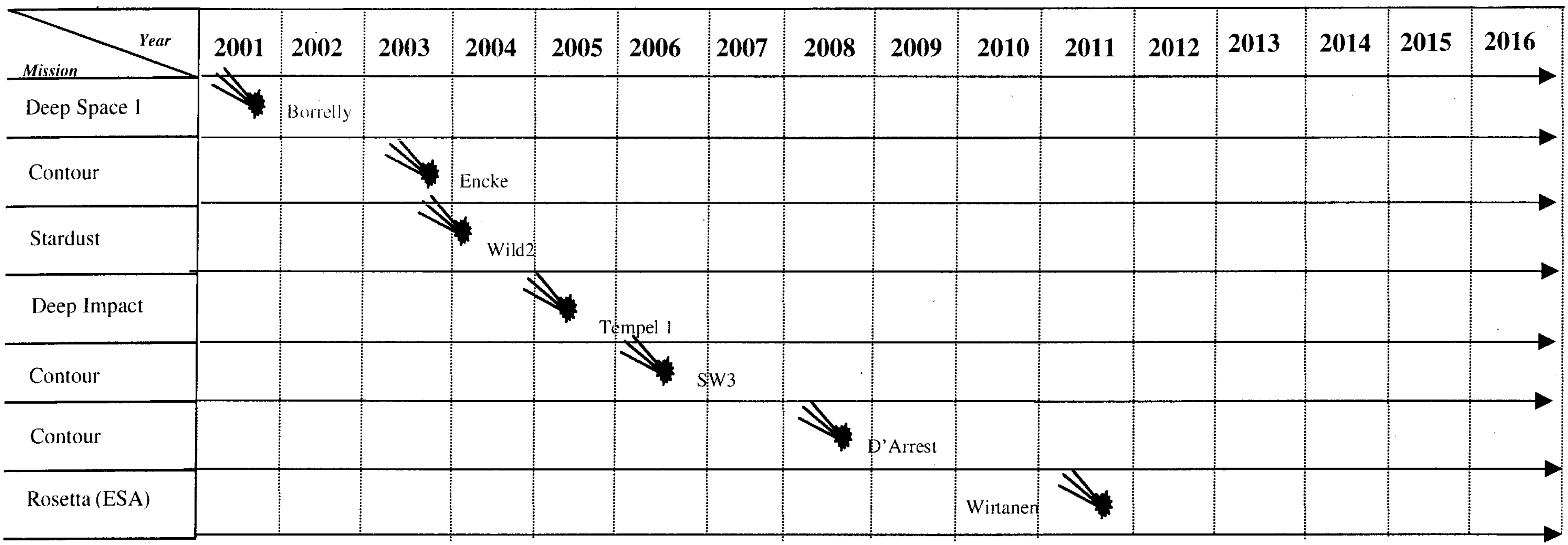
- Use of SEP for both outbound and return trajectories
  - SEP provides best mass performance and flight time
  - Dust may affect solar array performance, esp. if single s/c option

- Return to comet explored in prior mission or select unexplored target

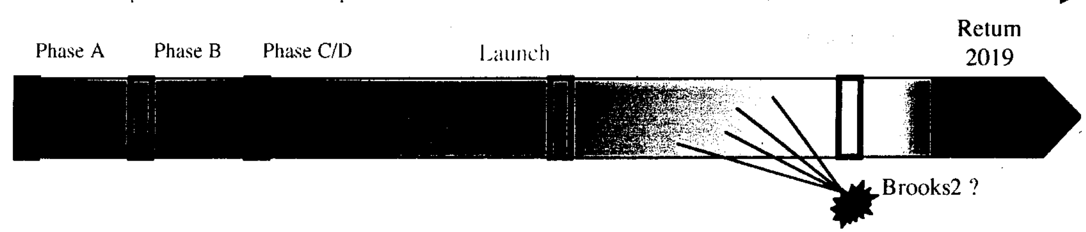
Comet Nucleus Sample Return

CNSR in the Sequence of Comet Exploration Missions

- CNSR launch opportunities occur almost every year
- Launch as early as 2007 - 2008 is feasible, depending on science and sampling goals
- Key project decisions should build on results of current/planned comet missions
- Coordination with MSR sample handling and analysis facilities will reduce costs



CNSR Example:
2011 launch to
Comet Brooks 2



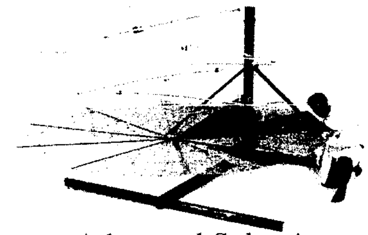
Comet Nucleus Sample Return

Major or Unique Developments Required

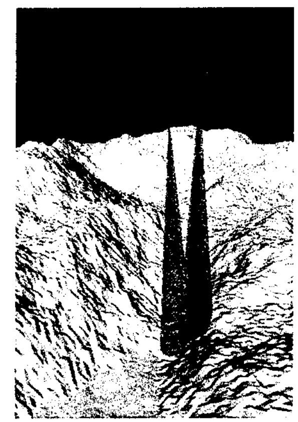
- Anchoring and drilling systems (prototypes developed under ST4)
- Sample transfer and cryogenic maintenance
- Dust mitigation techniques
- Development of cometary simulants for test and validation
- Precision guidance and landing
- Validation of Earth re-entry materials for higher velocities
- Terrestrial sample handling and analysis facilities

Heritage and Commonality

- Significant progress in designing and prototyping hardware was made during ST4 mission development
- Commonality with Mars Sample Return, esp. in guidance/landing, rendezvous and docking, sample transfer, ground facilities
- Stardust/Genesis Earth re-entry vehicle and techniques
- DS1 validation of SEP and subsequent ground testing



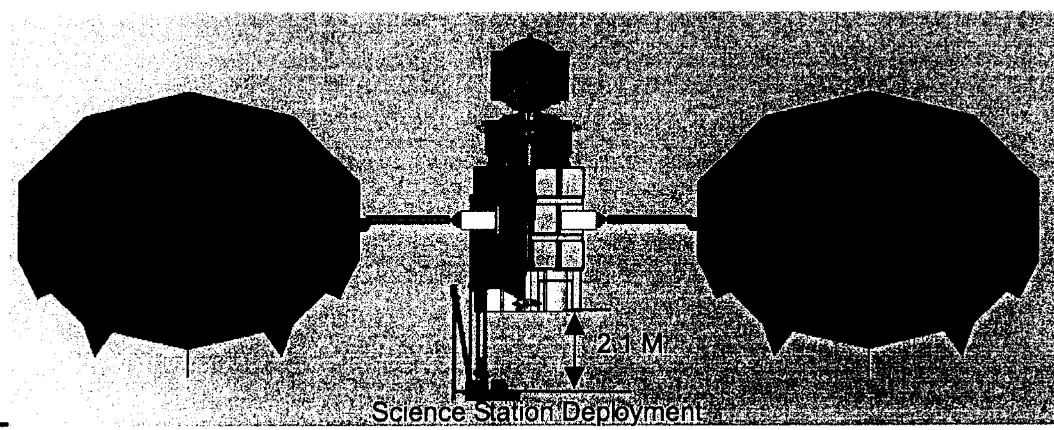
Advanced Solar Array



Precision Guidance and Landing

Next Generation SEP

Single Spacecraft - Landed Configuration



Comet Nucleus Sample Return

Comments and Issues

- CNSR fits logically within the progression of comet exploration missions:

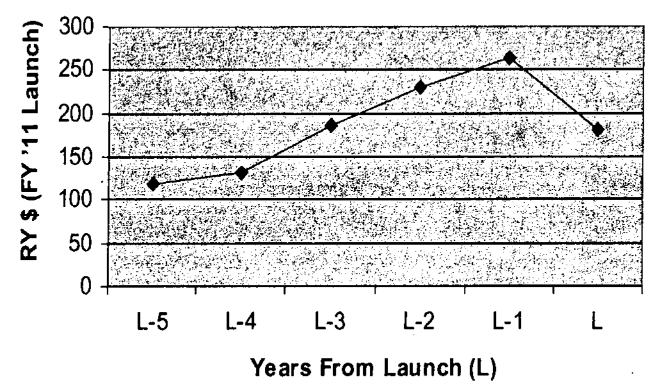
Basic nature of the nucleus	Giotto, DS1
Diversity of comets	CONTOUR
Nature of the dust/coma	Stardust
Internal strength/structure	Deep Impact
Active surface processes	Rosetta
Volatile inventory	CNSR

- CNSR is one of the few missions to outer solar system destinations that does not require RTGs
- Wide range of science/risk/cost options can be explored; key driver is surface vs. drilled sample and cryogenic preservation
- Ground sample handling costs not estimated; expect significant leverage with MSR
- Multimission technology development costs ~$45M for key technologies
- Mission class: Moderate to large
- Technology risk: Moderate

Cost (RY$, FY11 launch)

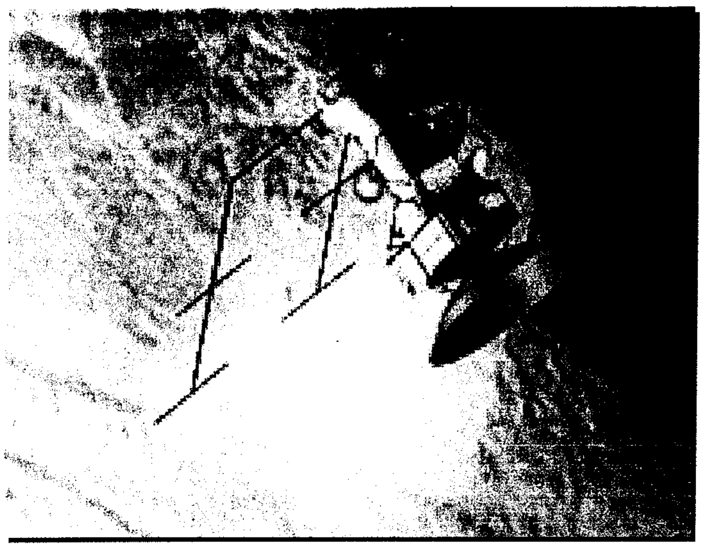
Development/launch: $500-1000M (depending on science reqmts)

Mission operations: $75-150 M



Solar System Exploration

Europa Orbiter



Objectives

Conduct intensive orbital study of Europa to conclusively determine presence or absence of subsurface ocean, understand formation and evolution of surface, and identify landing sites for possible future missions

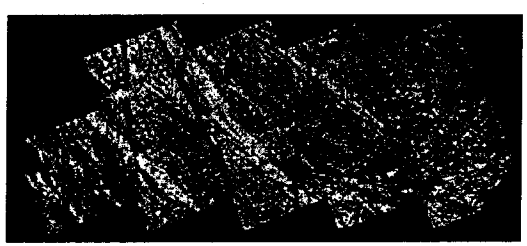
Mission scenario

- Delta-4H launch in 2008, direct to Jupiter (2.5 yrs)
- Propulsive capture into Jupiter orbit, 1.5 year gravity assist tour to reduce energy
- Propulsive capture into 200 km Europa orbit
- 30 day primary science mission, followed by maneuver to achieve quarantine orbit

Key Trades

- Earth gravity assist trajectory reduces launch vehicle size and increases mass margin, but increases flight time to Jupiter by 2 years

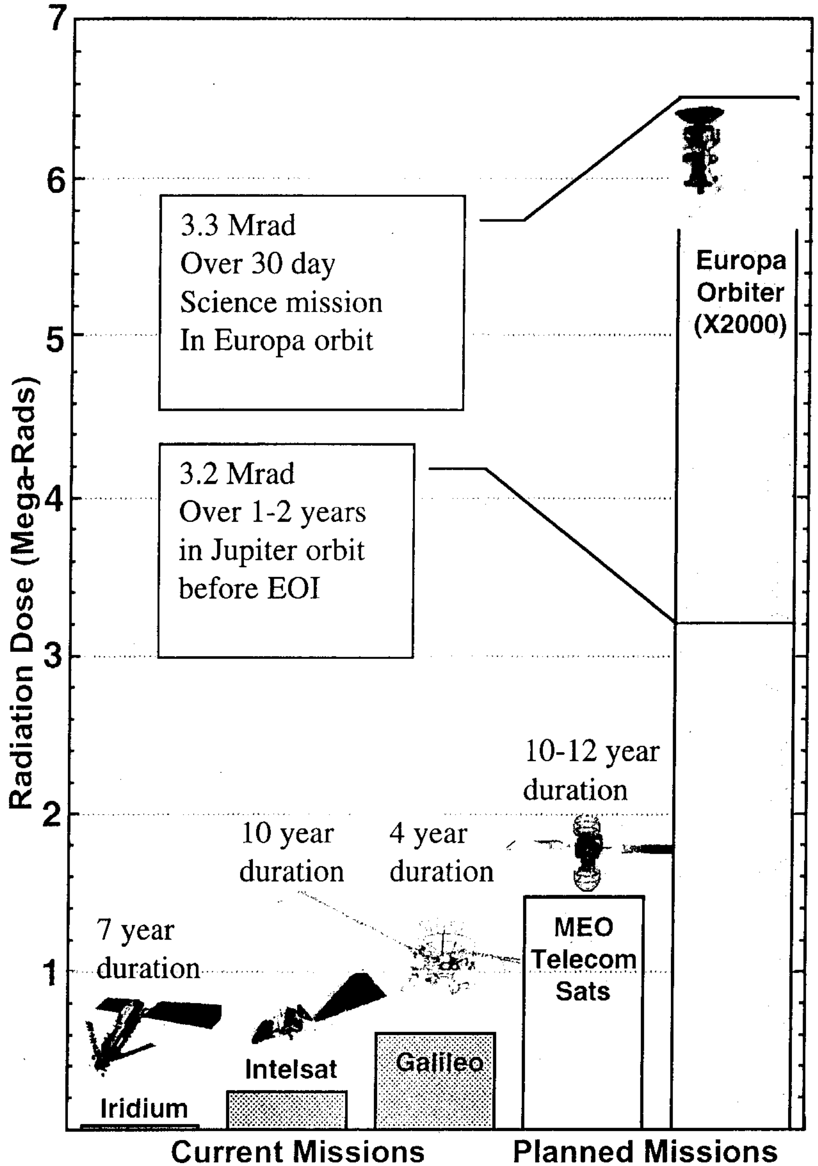
- Other Europa exploration modes (e.g. multi-flybys) have been examined as cost-reduction measures but would lead to significant reductions in primary science objectives



Solar System Exploration

Europa Orbiter

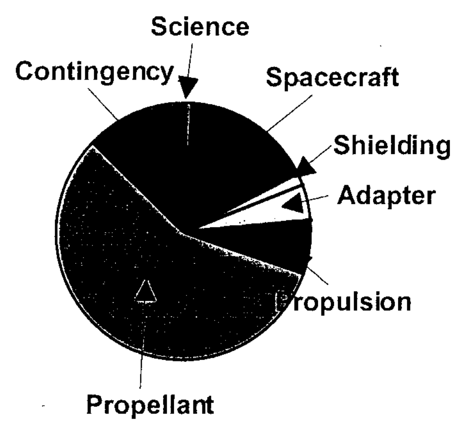
Challenges of Europa Environment



¥ The Europa Orbiter must operate with high reliability during the 30 day mission
  — Science objectives
  — Achieve quarantine orbit

¥ Delta-V requirements are very high

¥ Impact
  — New electronics technology development (X2000) to reduce mass and risk
  — Total shielding = 39 kg



MASS BREAKDOWN:

Science (allocation)	20 kg
Spacecraft (CBE)	354 kg
Rad shielding (CBE)	33 kg
Adapter (CBE)	90 kg
Propulsion Subsystem (CBE)	150 kg
Propellant (fully loaded)	1221 kg
Contingency (dry)	273 kg

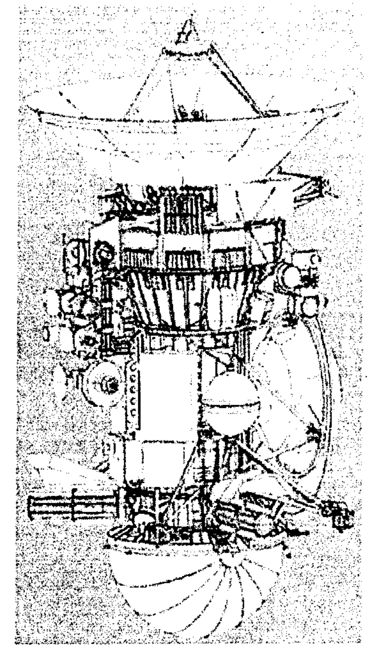
Europa Orbiter

Major or Unique Developments Required

- X2000 avionics for survival in Europa radiation environment - low mass and power
- Radiation-tolerant sensors and instruments
- Advanced radioisotope power source (may be required)

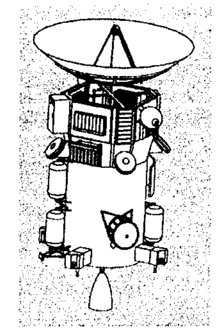
Heritage and Commonality

- Cassini spare RTGs are baseline
- Main engine, antenna, various subsystems inherited
- X2000 avionics has very wide applicability throughout space science program - baselined for Deep Impact, Starlight, SIM, Mars Smart Lander; various DOD, NOAA, industry uses considered



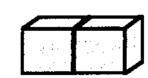
Cassini
22.3 ft (6.7 m)

Europa Orbiter
11.4 ft (3.5 m)



Cassini Bays

X2000 Chassis



Cassini Bays		X2000 Chassis
170 kg	*Mass*	43 kg
$0.25 m^3$	*Volume*	$0.074 m^3$
1 MIPS	*Processing speed*	60-200 MIPS

Solar System Exploration

Europa Orbiter

Comments and Issues

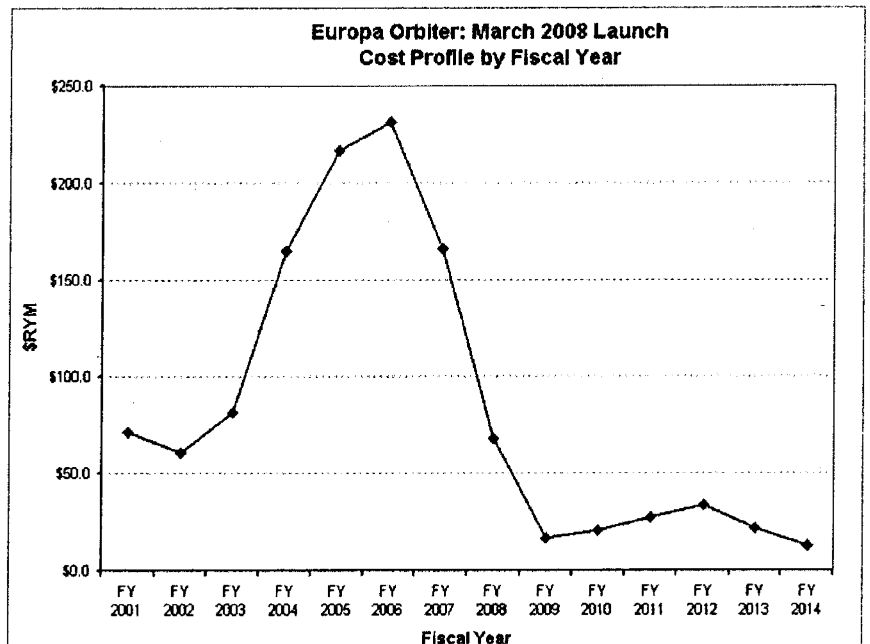
- Independent panels have identified a Europa orbiter as the only mission that can reliably achieve the primary science objectives
- Independent cost assessments show very good agreement with project cost estimates
- X2000 avionics technology has been selected for a number of space science missions; significant industry interest
- Primary remaining project risks are launch vehicle certification and cost, radioisotope power source selection, completion of X2000 avionics, and understanding of radiation effects

- Mission class: Large
- Technology risk: Moderate (on tasks to go)

Cost (from May 2001)

Development	$760M
Launch vehicle	170
Operations	120
Subtotal	**1050**
Taxes and fees	30
Total life cycle	$1080M

Notes:
- Includes X2000 completion costs
- Includes reserves and contingency
- Includes RTG ($67M)



Solar System Exploration

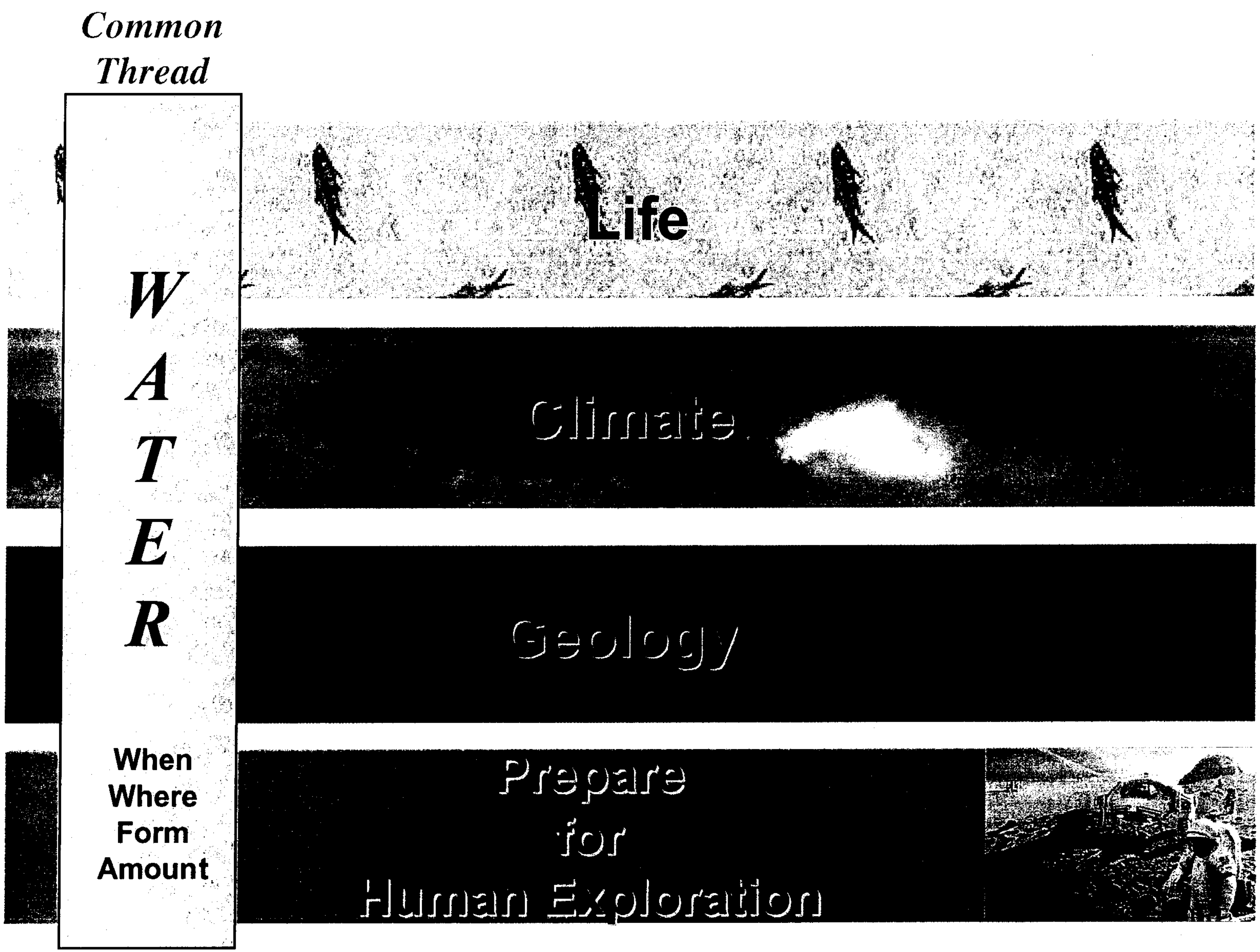
Recommendations on the Mars Program:

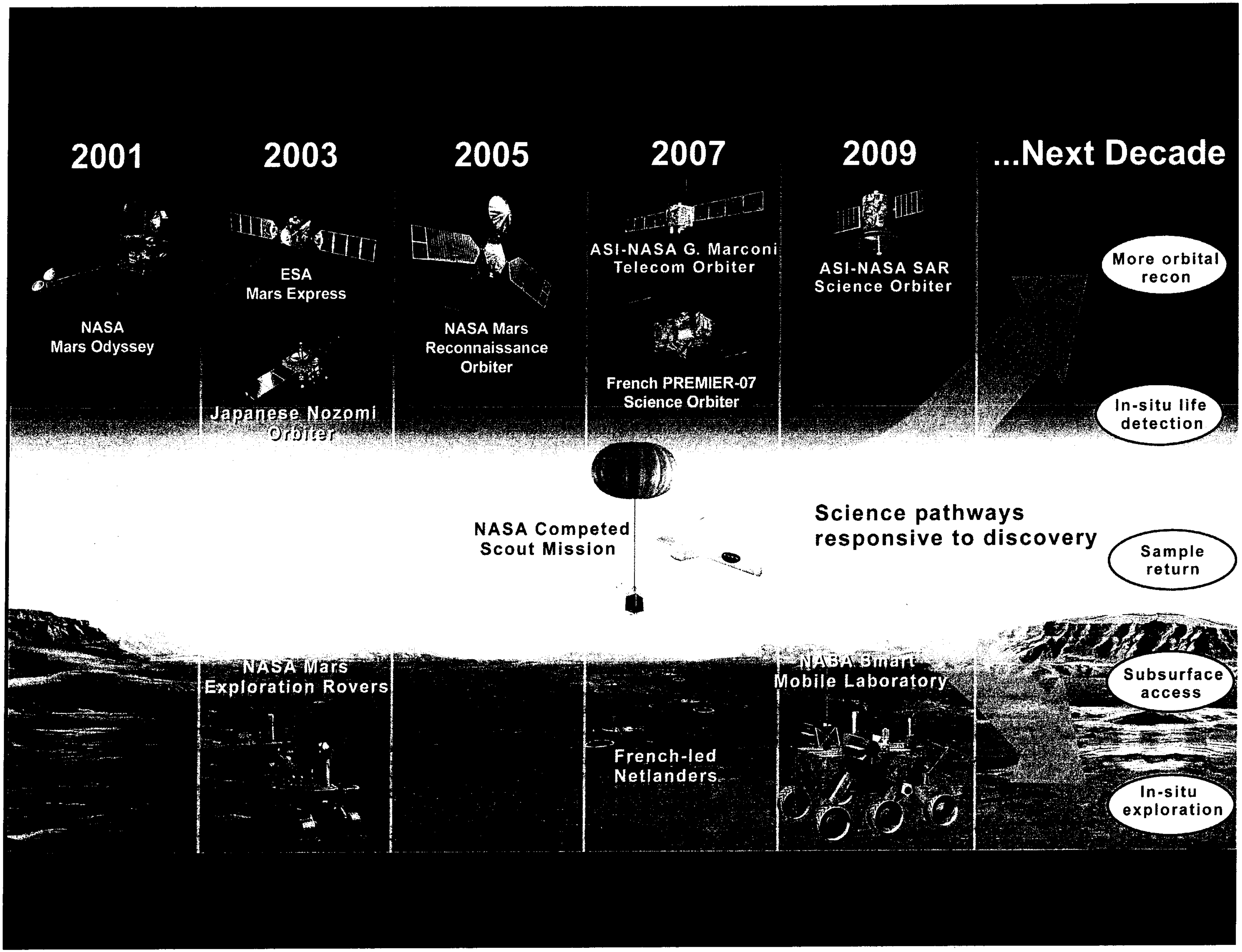
¥ We endorse the current science-driven strategy of ***seeking, in situ measurements, and sampling*** to understand Mars as a planet and to understand its astrobiological significance

¥ We recommend that NASA begin its planning for **Mars Sample Return (MSR)** missions so that their implementation can occur early in the decade 2013-2023

¥ We support the initiation of a series of small-class **Mars Scout** missions for flights at alternating Mars launch opportunities in a program modeled on the Discovery program.

The Mars Science Strategy: "Follow the Water"





2001
2003
2005
2007
2009
...Next Decade
NASA
Mars Odyssey
ESA
Mars Express
Japanese Nozomi
Orbiter
NASA Mars
Reconnaissance
Orbiter
ASI-NASA G. Marconi
Telecom Orbiter
French PREMIER-07
Science Orbiter
ASI-NASA SAR
Science Orbiter
More orbital
recon
In-situ life
detection
NASA Competed
Scout Mission
Science pathways
responsive to discovery
Sample
return
NASA Mars
Exploration Rovers
French-led
Netlanders
NASA Smart
Mobile Laboratory
Subsurface
access
In-situ
exploration

Solar System Exploration Survey:

This survey of Solar System Exploration —

¥ Provides a logical and compelling basis for flight mission selection based on profound motivational questions, clear scientific goals, and key scientific questions.

The survey s recommendations and priorities ensure:

¥ a vigorous flight program that will significantly address all of the key scientific questions identified for the coming decade

¥ a vital, productive, and creative infrastructure to support the flight program

¥ that essential technological developments will be pursued to support the recommended flight program and also provide a firm foundation for future Solar System Exploration